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A novel high speed fully differential CMOS amplifier

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Abstract : This paper describes a high speed fully differential CMOS amplifier in which positive feedback is employed to improve the operating frequency. By this process the delay time reduces and the speed of operation increases An even or odd number of stages can be cross coupled or directly coupled to form ring Voltage Controlled Oscillator or Current Controlled Oscillator (VCO/CCO) An improvement of speed of around 167% was obtained from circuit simulation (using PSPICE). Here the typical supply voltage requirement is ±2 volt Using this amplifier some applications are discussed

Keywords : Complimentary metal oxide semiconductor (CMOS), voltage controlled oscillator (VCO), current controlled oscillator (CCO), ring oscillator, phase locked loop (PLL)

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1. Introduction

Over the last few years there has been a rapid increase in chip complexity which has created the need to implement complete analog-digital subsystems on the same integrated circuit using the same technology. For this reason, implementation of analog functions in CMOS technology has become increasingly important [1,2].

This paper presents a high speed low voltage CMOS fully differential amplifier. The circuit features a positive feedback scheme to improve the speed and to reduce the supply voltage requirement of this amplifier (Figure 1). Since the circuit is fully differential, push-pull output is possible. To check the improvement in speed an even number of such amplifier stages have been cross coupled to form a ring oscillator (Figure 2), whose frequency depends on the delay time of each such amplifier stage. This ring oscillator also provides a quardrature output which is very much useful in various communication systems.

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In Section 2 detailed Mathematical Operation for decreasing delay time has been discussed. The simulated results of the fully differential CMOS amplifier are discussed in Section 3. Section 4 includes some applications of this amplifier.

2. Operation of delay time

Figure 1 gives the circuit diagram of the fully differential CMOS amplifier using positive feedback scheme. By introducing positive feedback the delay produced by each amplifier stage is reduced and hence the speed of operation increases [3] The frequency of oscillation depends on the number of the inverter stages, the load capacitances and the current level. It has been tested by connecting four such amplifier stages in series shown in Figure 2 and the outputs of the last stage are cross coupled with the inputs of the first stage.

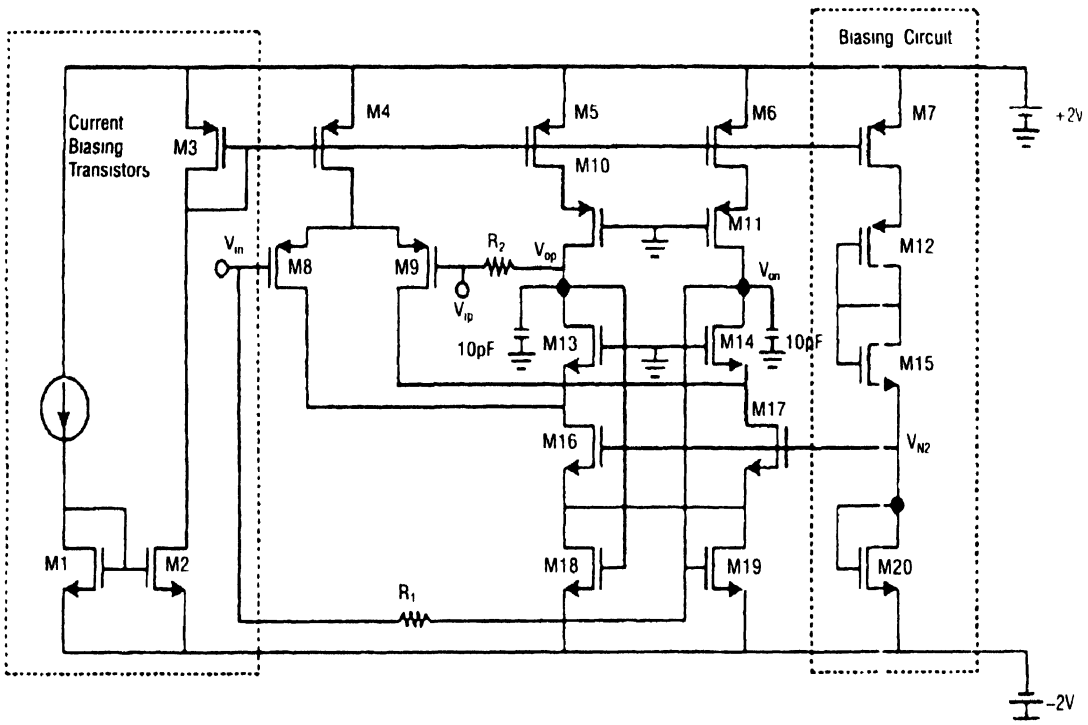

Figure 1. Circuit diagram of the fully differential CMOS amplifier with positive feedback.

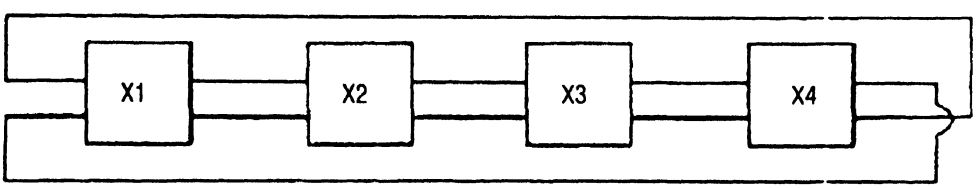

Figure 2. Block diagram of a 4-stage ring oscillator.

2 1 Calculation of phase factor without positive feedback :

For mathematical simplicity, we consider a simple CMOS operational amplifier with positive feedback shown in Figure 3. An AC small signal equivalent circuit of Figure 3 is shown in Figure 4.

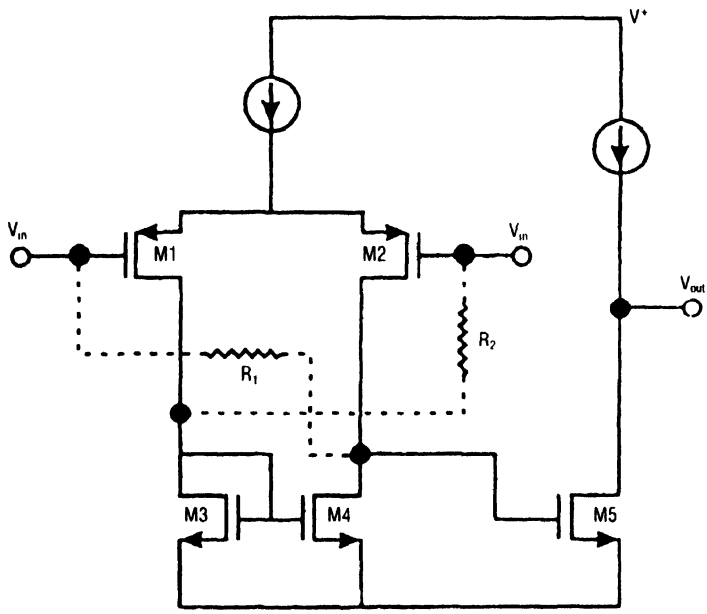

Figure 3. A simple CMOS operational amplifier.

The gain of this amplifier (from Figure 4) is

$$A_v = \frac{\mu R_4}{R_4 + r_1' + r_2'}$$

where r_1' and r_2' are the parallel combination of r_1, c_1 and r_2, c_2; R_3, R_4 are the effective drain resistances of MOSFETs M_3 and M_4 respectively. g_{m1} and g_{m2} are the transconductances of M_1 and M_2, r_1 and r_2 are the drain resistances of M_1 and M_2, c_1 and c_2 are the drain-source capacitances of M_1 and M_2 respectively. μ is the amplification factor.

So,

$$r_1' = \frac{r_1}{1 + j\omega c_1 r_1} \quad \text{and} \quad r_2' = \frac{r_2}{1 + j\omega c_2 r_2}$$

Now,

$$A_v = \frac{\mu R_4}{R_4 + \dfrac{r_1}{1 + j\omega c_1 r_1} + \dfrac{r_2}{1 + j\omega c_2 r_2}}$$

After calculation the phase factor without positive feedback is

$$\tan\phi = \frac{\omega r_1^2 c_1\left(1+\omega^2 c_2^2 r_2^2\right)+\omega r_2^2 c_2\left(1+\omega^2 c_1^2 r_1^2\right)}{R_4\left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right)+r_1\left(1+\omega^2 c_2^2 r_2^2\right)+r_2\left(1+\omega^2 c_1^2 r_1^2\right)}$$

(see Appendix-I)

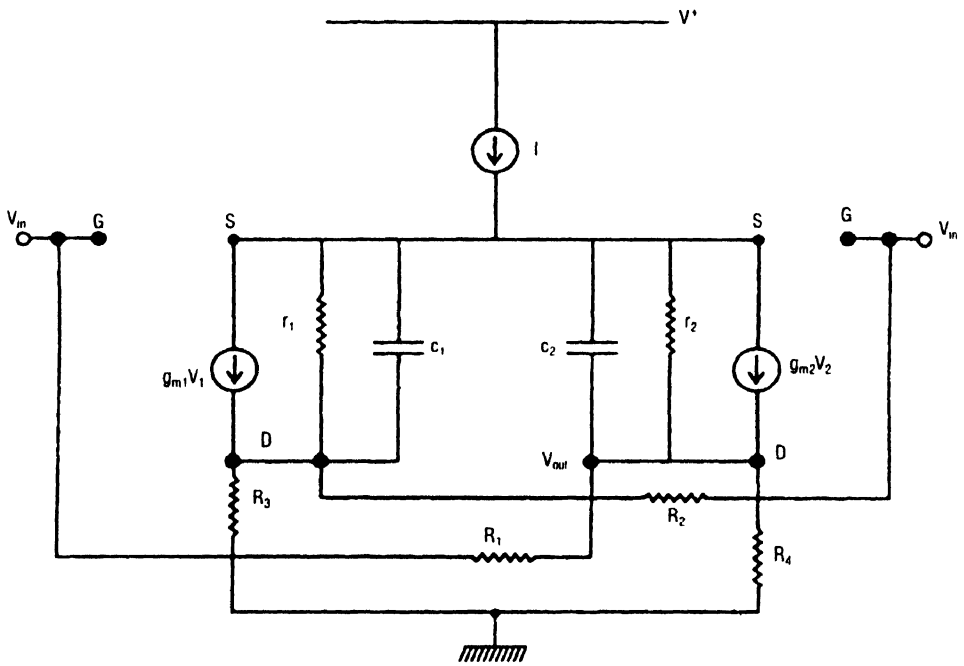

Figure 4. AC small signal equivalent circuit of Figure 3

2.2. Calculation of phase factor with positive feedback :

In the presence of positive feedback resistances, the overall gain of the amplifier will be $A_f = \frac{A}{1+\beta A}$, where β is the feedback ratio and 'A' is gain of the amplifier without positive feedback.

From Figure 4 we can write,

$\beta = \frac{R_l}{R_1 + R_l}$, where R_l is the impedance of the next stage, and $R_l \rangle 0$.

Now,

$$A_f = \frac{A}{1+\beta A}$$

After calculation the phase factor with positive feedback is

$$\tan\phi' = \frac{(R_1+R_l)\left(1+\omega^2c_2^2r_2^2\right)\omega c_1r_1^2+(R_1+R_l)\left(1+\omega^2c_1^2r_1^2\right)\omega c_2^2r_2^2}{\left[\mu R_4\left(1+\omega^2c_1^2r_1^2\right)\left(1+\omega^2c_2^2r_2^2\right)+R_4\left(1+\omega^2c_1^2r_1^2\right)\left(1+\omega^2c_2^2r_2^2\right)\right.}$$

$$\left.+r_1\left(1+\omega^2c_2^2r_2^2\right)+r_2\left(1+\omega^2c_1^2r_1^2\right)\right]R_l$$

$$+\left[R_4\left(1+\omega^2c_1^2r_1^2\right)\left(1+\omega^2c_2^2r_2^2\right)+r_1\left(1+\omega^2c_2^2r_2^2\right)\right.$$

$$\left.+r_2\left(1+\omega^2c_1^2r_1^2\right)\right]R_1 \qquad \text{(see Appendix-II)}$$

If $R_1 = \infty$ *i.e.* without positive feedback

$$\tan\phi' = \tan\phi$$

It is evident that $\tan\phi'$ ($\tan\phi$, *i.e.* the phase factor without positive feedback is greater than that with positive feedback. Hence with positive feedback, the delay time reduces compared to that without positive feedback and the speed of operation increases.

The same treatment can be applied to the fully differential amplifier circuit of Figure 1 with positive feedback and we will get a similar result. That is, with the application of positive feedback, delay produced by each inverter of Figure 2 will decrease and hence the speed of the inverter will increase.

3. Simulated results

The simulated results for percentage speed improvement with positive feedback resistance for a particular bias current of 25 μA is shown in Figure 5. This has been tested by connecting four such amplifier stages in series and the outputs of the last stage are cross coupled with the inputs of the first stage (Figure 2). The frequency of oscillation depends on the number of inverter stages, the load capacitances and the current level. This graph indicates that the percentage of frequency improvement is maximum for feedback resistance of 33 kΩ. For this case an improvement of speed of around 167% is obtained. Since each amplifier provides push-pull output, the quadrature and multiphase signals can be obtained from such a ring oscillator. Simulated quadrature output waveforms (for feedback resistance of 33 kΩ) are shown in Figure 6. These multiphase signals are very useful in communication systems.

The variation of frequency of oscillation of the above 4-stage ring oscillator with bias current for a particular feedback resistance of 47 kΩ is shown in the Figure 7. Since the variation is linear over a wide range of current from 25 μA to 50 μA, the circuit can be very effectively used as current controlled oscillator (CCO) and is suitable for Phase Locked Loop (PLL) applications.

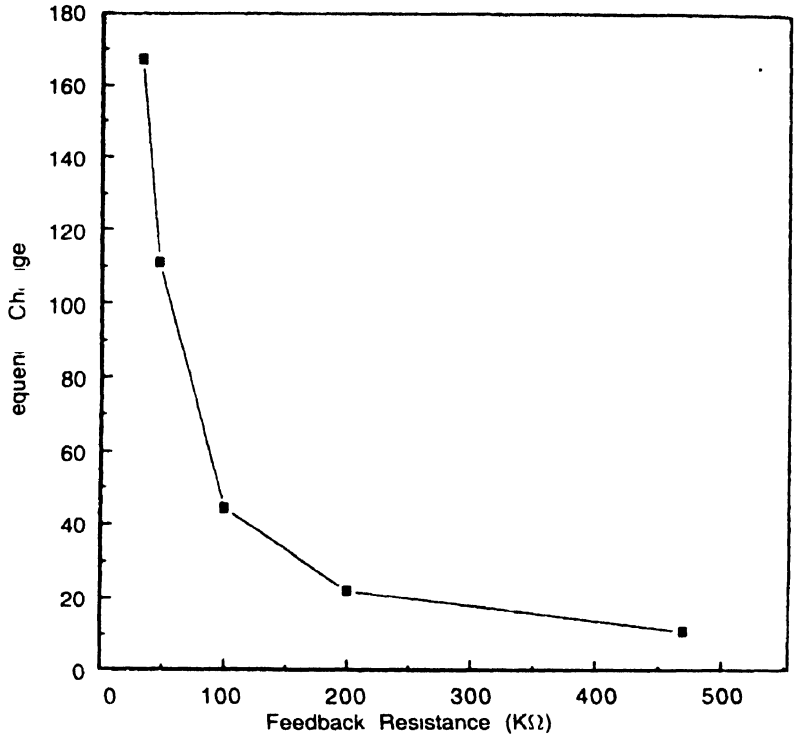

Figure 5. Percentage of speed improvement with feedback resistance

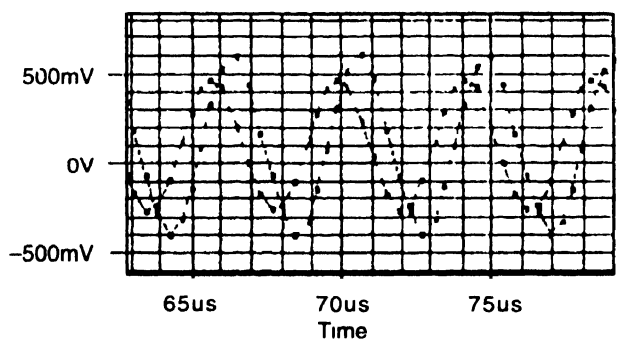

Figure 6. Simulated quadrature output waveforms of the 4-stage ring oscillator

4. Application of the proposed VCO using MOSFETS

In wireless communication systems, *e.g.* portable voice, data and messaging systems, VCO is an essential part. Frequency synthesizers consisting of VCO, reference oscillator, programmable counters are an integral part of transceivers [4]. Modern communication circuits such as integrated radio paging receivers, QPSK modulators, harmonic generators *etc.* need quadrature/multiphase outputs. Synchronized/phase locked oscillators are widely used for suppression of noise and interference in an incoming signal [5–9]. Phase locked loops provide multiphase clock signals in digital circuits [10–14]. Multiphase outputs are also required in coherent PSK reception.

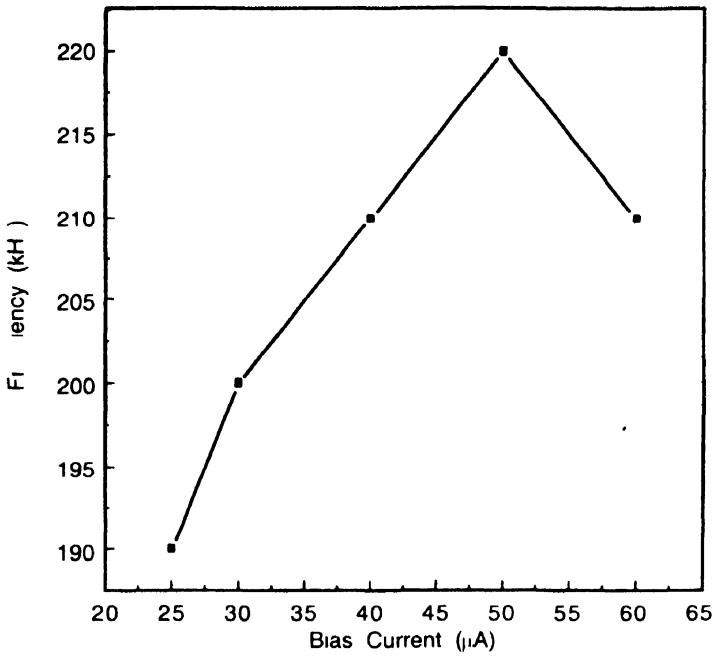

Figure 7. Frequency change with bias current for a feedback resistance of 47 kΩ

These multiphase/quadrature outputs may be realized using ring oscillator VCOs as described in Figure 2

4 1 Multiphase/quadrature signal generation

The extremely accurate phase tracking capabilities of Charge-pump PLLs help us to generate multiphase non-overlapping clocks [15–19]. For this case, the VCO should comprise of a multistage tapped delay line that is automatically calibrated to a precise delay per stage [20], The generation of arbitrary multiphase clocks is possible with proper decoding of the signals from the delay line-taps. In many telecommunication applications (*e.g.* synchronous detectors) signals that are in quadrature are needed Such quadrature outputs are generated using the 4-stage ring oscillator VCO as shown in Figure 2. The signals obtained from the outputs of stages X2 and X4 are in phase quadrature and are shown in Figure 6. Note that the frequency of oscillation obtained without positive feedback is only 90 KHz at 25 μA, but with positive feedback (using 33 kΩ resistance) it increases to 240 KHz at the same current

4 2 Zero_IF receiver using quadrature signals

Figure 8 shows a block diagram of the paging receiver. The incoming *RF* signals are mixed in two mixers-one mixer is fed with the in-phase component of a push-pull type ring oscillator VCO (used as local oscillator) and the other is fed with its quadrature output. The VCO is normally operated at the centre frequency of the received signal. At the output of the mixers, two low pass filters are there. These filters have a pass

bandwidth of one half the bandwidth of the *RF* signal spectrum, since information from both the high side and low side of the local oscillator is folded over into this frequency band. The low frequency output from the mixers, after selection by these filters are fully limited in two high gain limiting amplifiers and then treated as digital signals and processed by a digital demodulator which consists in its most simple form of a D-type flip-flop, as shown in Figure 8.

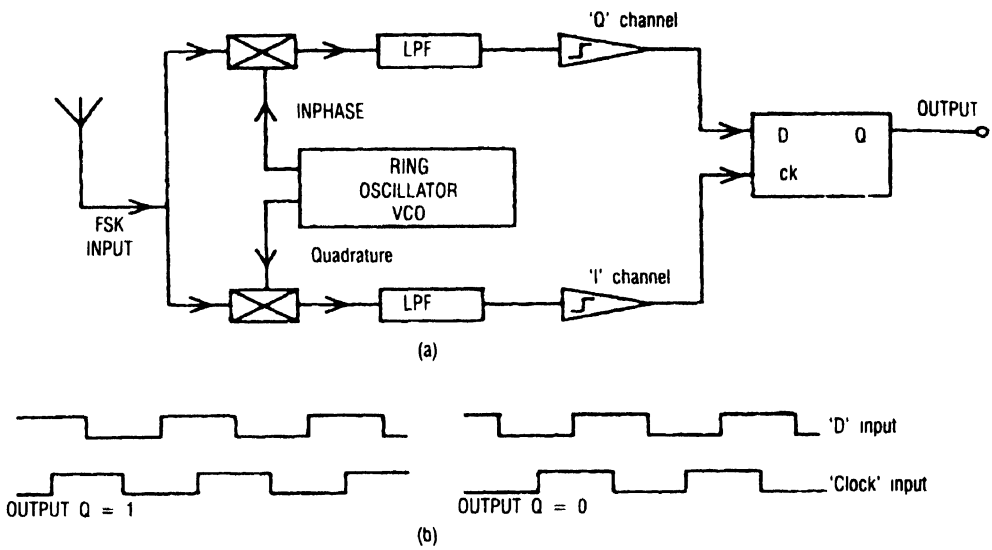

Figure 8. (a) Block diagram of a zero-IF paging receiver and (b) waveform of the zero-IF paging receiver

5. Conclusion

A high frequency fully differential CMOS amplifier with positive feedback has been simulated using PSPICE. An even number of such stages have been cross connected to form a ring oscillator. Simulated results showed, due to the application of positive feedback, a maximum of 167% increase in speed with feedback resistance of 33 kΩ. This improved amplifier can operate with a supply voltage of ± 2.0 volts. Current tuning characteristics of the ring oscillator is linear over a wide range of current, suitable for PLL applications. The presented circuit is highly suitable for VLSI integration, where the operating speed can be much higher, depending upon device dimension.

Acknowledgment

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Appendix-I

$$A_v = \frac{\mu R_4}{R_4 + \dfrac{r_1(1-j\omega c_1 r_1)}{1+\omega^2 c_1^2 r_1^2} + \dfrac{r_2(1-j\omega c_2 r_2)}{1+\omega^2 c_2^2 r_2^2}} \tag{1}$$

$$= \frac{\mu R_4 \left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right)}{R_4\left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right) + r_1\left(1+\omega^2 c_2^2 r_2^2\right)\left(1-i\omega c_1 r_1\right) + r_2\left(1+\omega^2 c_1^2 r_1^2\right)(1-j\omega c_2 r_2)}$$

$$= \frac{\mu R_4 \left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right)}{R_4 + \left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right) + r_1\left(1+\omega^2 c_2^2 r_2^2\right) + r_2\left(1+\omega^2 c_1^2 r_1^2\right) - j\left\{\omega r_1^2 c_1\left(1+\omega^2 c_2^2 r_2^2\right) + \omega r_2^2 c_2\left(1+\omega^2 c_1^2 r_1^2\right)\right\}}$$

$$= \frac{X}{Y - jZ} \tag{2}$$

where

$$X = \mu R_4 \left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right)$$

$$Y = R_4\left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right) + r_1\left(1+\omega^2 c_2^2 r_2^2\right) + r_2\left(1+\omega^2 c_1^2 r_1^2\right)$$

and

$$Z = \left\{\omega r_1^2 c_1\left(1+\omega^2 c_2^2 r_2^2\right) + \omega r_2^2 c_2\left(1+\omega^2 c_1^2 r_1^2\right)\right\}$$

So, the phase factor

$$\tan\phi = Z/Y$$

$$\tan\phi = \frac{\omega r_1^2 c_1\left(1+\omega^2 c_2^2 r_2^2\right) + \omega r_2^2 c_2\left(1+\omega^2 c_1^2 r_1^2\right)}{R_4\left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right) + r_1\left(1+\omega^2 c_2^2 r_2^2\right) + r_2\left(1+\omega^2 c_1^2 r_1^2\right)}$$

Appendix-II

$$A_f = \frac{A}{1+\beta A} \tag{3}$$

$$= \frac{\dfrac{X}{Y - jZ}}{1 + \dfrac{X}{Y - jZ} \times \left(\dfrac{R_l}{R_1 + R_l} \right)}$$

$$= \frac{\dfrac{X}{Y - jZ}}{\dfrac{(Y - jZ)(R_1 + R_l) + XR_l}{(Y - jZ)(R_1 + R_l)}}$$

$$= \frac{X(R_1 + R_l)}{(Y - jZ)(R_1 + R_l) + XR_l}$$

$$= \frac{X(R_1 + R_l)}{YR_1 + YR_l - jZR_1 - jZR_l + XR_l}$$

$$= \frac{X(R_1 + R_l)}{(X + Y)R_l + YR_1 - j(R_1 + R_l)Z}$$

$$= \frac{\mu R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right)(R_1 + R_l)}{\left[\left\{\mu R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right) + R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right)\right.\right.}$$
$$\left. + r_1 \left(1 + \omega^2 c_2^2 r_2^2\right) + r_2 \left(1 + \omega^2 c_1^2 r_1^2\right)\right\} R_l$$
$$\left. + \left\{R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right) + r_1 \left(1 + \omega^2 c_2^2 r_2^2\right) + r_2 \left(1 + \omega^2 c_1^2 r_1^2\right)\right\} R_1\right]$$
$$- j\left[\left\{\left(1 + \omega^2 c_2^2 r_2^2\right)\omega c_1 r_1^2 + \left(1 + \omega^2 c_1^2 r_1^2\right)\omega c_2 r_2^2\right\}(R_1 + R_l)\right]$$

Putting the values of X, Y and Z from eq. (2)

$$= \frac{X'}{Y' - jZ'} \tag{4}$$

where

$$X' = \mu R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right)(R_1 + R_l)$$

$$Y' = \left[\left\{\mu R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right) + R_4 \left(1 + \omega^2 c_1^2 r_1^2\right) \times \left(1 + \omega^2 c_2^2 r_2^2\right)\right.\right.$$
$$\left. + r_1 \left(1 + \omega^2 c_2^2 r_2^2\right) + r_2 \left(1 + \omega^2 c_1^2 r_1^2\right)\right\} R_l + \left\{R_4 \left(1 + \omega^2 c_1^2 r_1^2\right)\left(1 + \omega^2 c_2^2 r_2^2\right)\right.$$
$$\left. + r_1 \left(1 + \omega^2 c_2^2 r_2^2\right) + r_2 \left(1 + \omega^2 c_1^2 r_1^2\right)\right\} R_1\Big].$$

$$Z' = \left[\left\{\left(1+\omega^2 c_2^2 r_2^2\right)\omega c_1 r_1^2 + \left(1+\omega^2 c_1^2 r_1^2\right)\omega c_2 r_2^2\right\}\left(R_1 + R_l\right)\right]$$

The phase factor with positive feedback is $\tan\phi' = \dfrac{Z'}{Y'}$

$$\tan\phi' = \frac{\left(R_1 + R_l\right)\left(1+\omega^2 c_2^2 r_2^2\right)\omega c_1 r_1^2 + \left(R_1 + R_l\right)\left(1+\omega^2 c_1^2 r_1^2\right)\omega c_2 r_2^2}{\begin{aligned}&\mu R_4\left(1+\omega^2 c_1^2 r_2^2\right)\left(1+\omega^2 c_2^2 r_2^2\right) + R_4\left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right)\\ &+ r_1\left(1+\omega^2 c_2^2 r_2^2\right) + r_2\left(1+\omega^2 c_1^2 r_1^2\right)\Big] R_l +\\ &R_4\left(1+\omega^2 c_1^2 r_1^2\right)\left(1+\omega^2 c_2^2 r_2^2\right) + r_1\left(1+\omega^2 c_2^2 r_2^2\right) + r_2\left(1+\omega^2 c_1^2 r_1^2\right)\Big] R_1\end{aligned}} \tag{5}$$